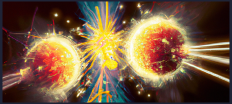
⊙ Thermalization of a hard parton in a QCD plasma



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Based on:

- C. Sirimanna et al. arXiv:2211.15553
- Y. Mehtar-Tani, S. Schlichting, and IS arXiv:2209.10569
- S. Schlichting, IS JHEP 07 (2021), 077

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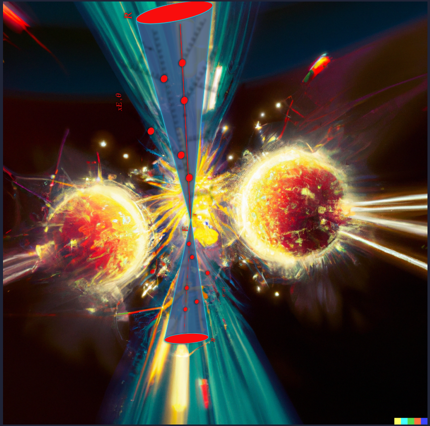
- Introduction
- Effective Kinetic Description
- Longitudinal Energy Loss
- Thermalization To Large Angles
- Flavor Composition Of The Shower

Introduction I

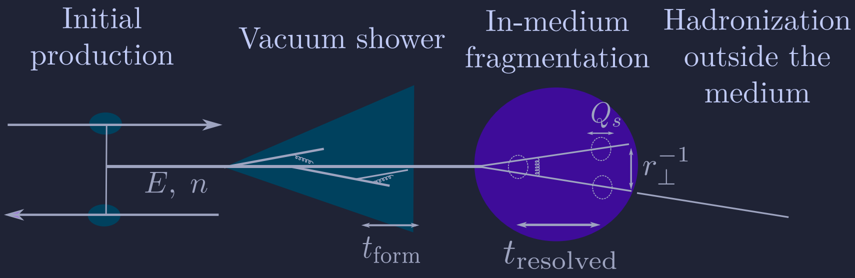


During heavy ion collisions:

- Deconfined Quark-Gluon Plasma (QGP) is created
  $\Rightarrow$ Elliptic flow, Jet quenching
- Hard partons created at early stages
- They must traverse the QCD plasma, before reaching the detector
- By interacting with the medium, they probe the non-equilibrium evolution of the QCD fireball

[0] Image generated using DALL-E.

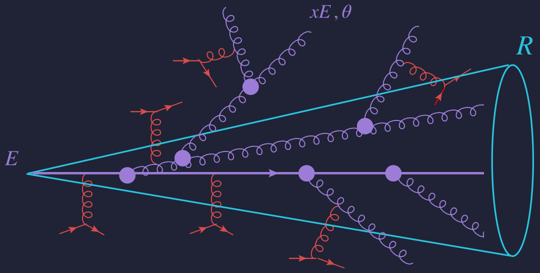
⊙ Introduction II



» The evolution of a hard parton during heavy ion collisions

» We focus on energy loss and equilibration of hard partons once resolved by the medium

⊙ In-Medium Shower



» Main focus: Hard parton traversing a QCD plasma

» Understand: Energy cascade, out-of-cone energy loss, medium response and full thermalization of the shower ⇒ Important for low energy jets

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Effective Kinetic Description

- Based on an effective kinetic theory at leading order:

$$p^\mu \partial_\mu f_i(\vec{x}, \vec{p}, t) = C_i[\{f_i\}] \,, \tag{1}$$

- The hard partons are described as linearized fluctuations around the equilibrium distribution

$$f(p, t) = n_{eq}(p, t) + \delta f_{jet}(p, t) \,, \tag{2}$$

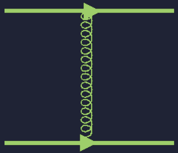
- We define energy distribution

$$D(x, \theta, t) \equiv x \frac{dN_a}{dx d\cos\theta} \sim \frac{\nu_a(N_f)}{E_j} \delta f_{jet}(p, \theta, t) \,. \tag{3}$$

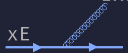
- Exact conservation of energy, momentum and valence charge → Allow us to study the evolution from $\sim E$ to $\sim T$ including full thermalization

Effective Kinetic Description

» Elastic Scatterings using HTL screened $2 \leftrightarrow 2$



» Collinear Radiation effective $1 \leftrightarrow 2$



$$C[\{f_i\}] = C^{2\leftrightarrow 2}[\{f_i\}] + C^{1\leftrightarrow 2}[\{f_i\}]\,. \tag{4}$$

» Similar to thermalization of QGP in pre-Hydro studies

Elastic Scattering

Collision integral for ellastic scattering using HTL screened matrix element

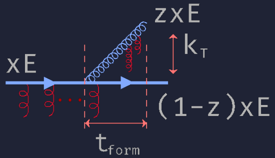
$$C_a^{2\leftrightarrow 2}[\{f_i\}] = \frac{1}{2|p_1|\nu_a}\sum_{bcd}\int d\Omega^{2\leftrightarrow 2}|\mathcal{M}^{ab}_{cd}(p_1,p_2,p_3,p_4)|^2\delta\mathcal{F}(p,p_1,p_2,p_3,p_4) \quad (5)$$

Keeping track of the medium response by including the full detailed balance terms

$$\begin{aligned}\delta F(p_1,p_2,p_3,p_4) = \quad & \delta f_a(p_1)[\pm_a n_c(p_3)n_d(p_4) - n_b(p_2)(1 \pm n_c(p_3) \pm n_d(p_4))] \\ & + \delta f_b(p_2)[\pm_b n_c(p_3)n_d(p_4) - n_a(p_1)(1 \pm n_c(p_3) \pm n_d(p_4))] \\ & - \delta f_c(p_3)[\pm_c n_a(p_1)n_b(p_2) - n_d(p_4)(1 \pm n_a(p_1) \pm n_b(p_2))] \\ & - \delta f_d(p_4)[\pm_d n_a(p_1)n_b(p_2) - n_c(p_3)(1 \pm n_a(p_1) \pm n_b(p_2))]\,. \end{aligned} \quad (6)$$

⊙ Collinear Radiation

» Multiple scatterings
$\Rightarrow$ induced radiation

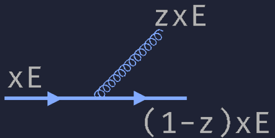


» Emission controlled by the formation time

$$t_{form} \sim \frac{z(1-z)xE}{k_T^2} \Rightarrow k_T^2 \sim \hat{q}t_{form} \quad (7)$$

$$t_{form} \sim \sqrt{\frac{z(1-z)xE}{\hat{q}}} \Rightarrow \hat{q} \sim \frac{m_D^2}{\lambda mfp} \quad (8)$$

» Resummed into an effective $1 \leftrightarrow 2$



» $t_{form} \ll \lambda_{mfp}$: Medium cannot resolve the quanta until it is formed

» $t_{form} \gg \lambda_{mfp}$: Multiple scatterings act coherently

» Coherence effects lead to suppression of high energy radiation
$\Rightarrow$ LPM effect

[0](Baier, Dokshitzer, Mueller, Peigné, Schiff, Zakharov, Wiedemann, Arnold, Moore, Yaffe..)

⊙ Collinear Radiation

Collinear radiation treated using the AMY formalism for an infinite medium (including BH & LPM effects)

$$
\begin{aligned}
C_g^{g\leftrightarrow gg}[\{D_i\}] = \int_0^1 dz \frac{d\Gamma^g_{gg}\left(\left(\frac{xE}{z}\right),z\right)}{dz} \Bigg[& D_g\left(\frac{x}{z}\right)\left(1 + n_B(xE) + n_B\left(\frac{\bar{z}xE}{z}\right)\right) \\
& + \frac{D_g(x)}{z^3}\left(n_B\left(\frac{xE}{z}\right) - n_B\left(\frac{\bar{z}xE}{z}\right)\right) + \frac{D_g\left(\frac{\bar{z}xE}{z}\right)}{\bar{z}^3}\left(n_B\left(\frac{xE}{z}\right) - n_B(xE)\right)\Bigg] \\
& - \frac{1}{2}\int_0^1 dz \frac{d\Gamma^g_{gg}(xE,z)}{dz}\Bigg[D_g(x)(1 + n_B(zxE) + n_B(\bar{z}xE)) \\
& + \frac{D_g(zx)}{z^3}(n_B(xE) - n_B(\bar{z}xE)) + \frac{D_g(\bar{z}x)}{\bar{z}^3}(n_B(xE) - n_B(zxE))\Bigg],
\end{aligned}
$$

» Including all the statistical factors which lead to thermalization of soft sector

⊙ Outline

- ⊙ Introduction
- ⊙ Effective Kinetic Description
- ⊙ Longitudinal Energy Loss
- ⊙ Thermalization To Large Angles
- ⊙ Flavor Composition Of The Shower

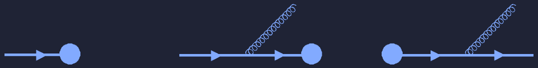
⊙ Longitudinal Energy Loss

» Evolution can be divided into three regimes:

1. Initial energy loss: mediated by single gluon radiation
2. Energy cascade: successive emissions lead to an energy cascade
3. Equilibration: Late time decay to soft sector

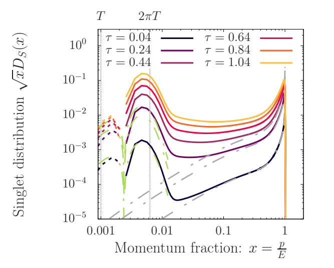
⊙ Single Emission

» Initial distribution determined from direct emissions



$$D_q(x,\tau) \simeq \quad \delta(1-x) \quad + \quad \left[x\frac{d\Gamma^q_{gq}(x)}{dz} - \int_0^1 dz \; z\frac{d\Gamma^q_{gq}(x,z)}{dz}\delta(1-x)\right]\tau \qquad (9)$$

» Short lived stage ⇒ Subsequent emissions lead to energy cascade



Energy Cascade

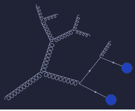
» Stationary turbulent solution in intermediate energy range $T/E \ll x \ll 1$:

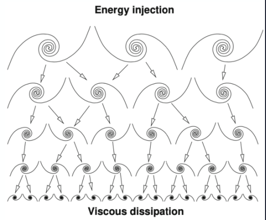
$$D_g(x) = \frac{G}{\sqrt{x}}, \qquad D_S(x) = \frac{S}{\sqrt{x}}. \tag{10}$$

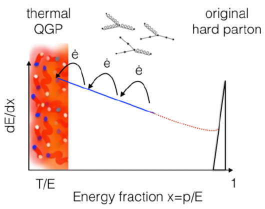
» Fixed point of the differential equaiton

$$\begin{aligned} C_g[\{D_i\}] &= \int_0^1 dz \, \frac{d\Gamma^g_{gg}\left(\frac{xE}{z}, z\right)}{dz} D_g\left(\frac{x}{z}\right) - \frac{1}{2} \frac{d\Gamma^g_{gg}(xE, z)}{dz} D_g(x) \\ &\quad + \int_0^1 dz \, \frac{d\Gamma^q_{gq}\left(\frac{xE}{z}, z\right)}{dz} D_S\left(\frac{x}{z}\right) - N_f \int_0^1 dz \, \frac{d\Gamma^g_{q\bar{q}}(xE, z)}{dz} D_g(x), \\ C_S[\{D_i\}] &= \int_0^1 dz \, \frac{d\Gamma^q_{gq}\left(\frac{xE}{z}, \bar{z}\right)}{dz} D_S\left(\frac{x}{z}\right) - \frac{d\Gamma^q_{gq}(xE, z)}{dz} D_S(x) \\ &\quad + 2N_f \int_0^1 dz \, \frac{d\Gamma^g_{q\bar{q}}\left(\frac{xE}{z}, z\right)}{dz} D_g\left(\frac{x}{z}\right), \end{aligned} \tag{11}$$

$$C_V[\{D_i\}] = \int_0^1 dz \, \frac{d\Gamma^q_{gq}\left(\frac{xE}{z}, \bar{z}\right)}{dz} D_V\left(\frac{x}{z}\right) - \frac{d\Gamma^q_{gq}(xE, z)}{dz} D_V(x), \tag{12}$$





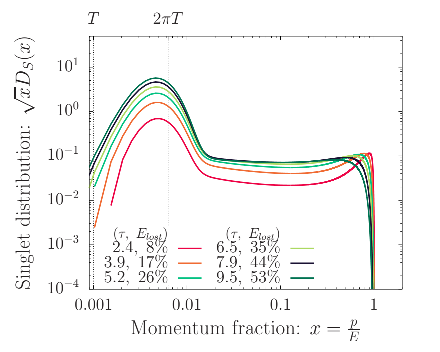


Energy Cascade

- Stationary turbulent solution in intermediate energy range $T/E \ll x \ll 1$:

$$D_g(x) = \frac{G}{\sqrt{x}}\,, \qquad D_S(x) = \frac{S}{\sqrt{x}}\,. \qquad (10)$$

- Existence of a fixed point of the differential equation comes from the fact that the rate behaves as $1/\sqrt{xE}$



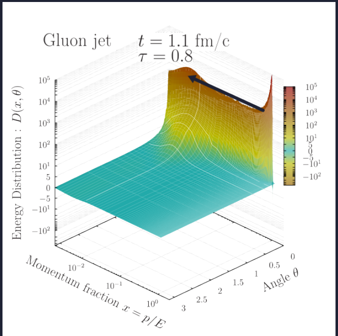
Outline

⊙ Thermalization To Large Angles

» Energy cascade to soft sector

» Broadening of soft partons to large angle

» Thermalization of soft sector



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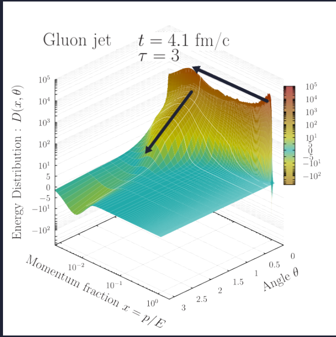
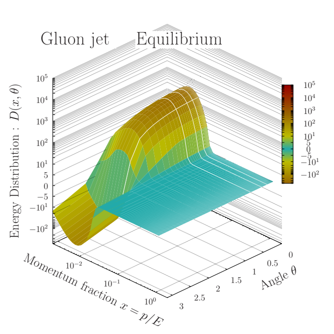




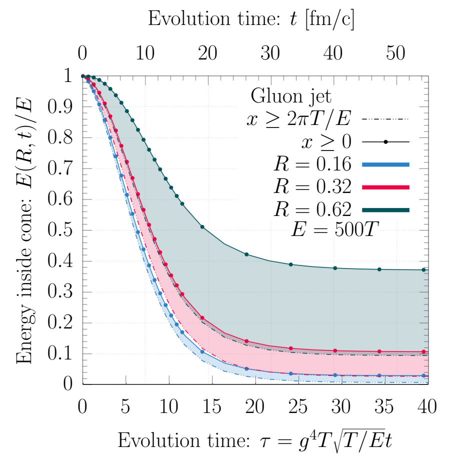
[1] $E/T = 500$, $g = 2$.

Cone-Size Dependence

—●— : $E(R,\tau) = \int_0^\infty dx \int_{\cos R}^1 d\cos\theta \; D(x,\cos\theta,\tau)$ (11)

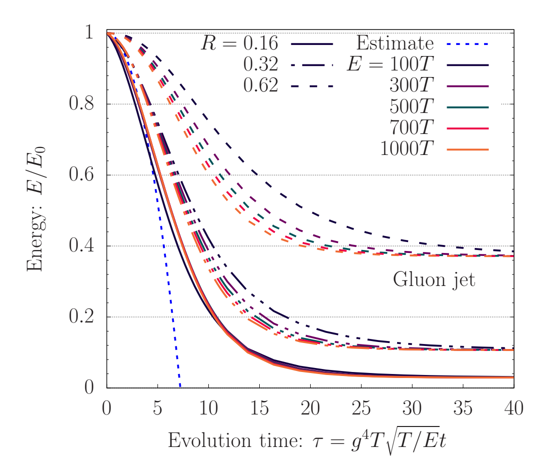
- Small cone-sizes: Soft sector does not play major role
- Large cone-sizes: Energy loss display different behavior ⇒ Dominated by thermalization

-·-·-· : $E_{2\pi}(R,\tau) = \int_{2\pi T/E}^\infty dx \int_{\cos R}^1 d\cos\theta \; D(x,\cos\theta,\tau)$ (12)



⊙ Sensitivity To Initial Parton's Energy

- Characteristic time of the turbulent cascade $t_{th} = \frac{1}{\alpha_s}\sqrt{\frac{E}{\hat{q}}}$
- Scaling between different initial parton's energy for small cone-sizes
- Broken for large cone-sizes



Modeling Jet Quenching

» In the presence of QGP, the jet spectrum factorizes

$$\frac{d\sigma}{dp_T} = \int_0^\infty d\epsilon \;\; P(\epsilon, R) \frac{d\sigma_{vac}}{dp_T^{in}} (p_T^{in} \equiv p_T + \epsilon), \tag{13}$$

» The energy loss probability $P(\epsilon, R)$ is obtained using the BDMPS rate

$$P(\epsilon, R) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \omega_i \frac{dI}{\omega_i} d\omega_i \right] \delta \left(\epsilon - \sum_{i=1}^{n} \omega_i \right) \exp \left[- \int_0^\infty d\omega \frac{dI}{d\omega} \right] \tag{14}$$

» Using a Milne transform ⇒ Exponential

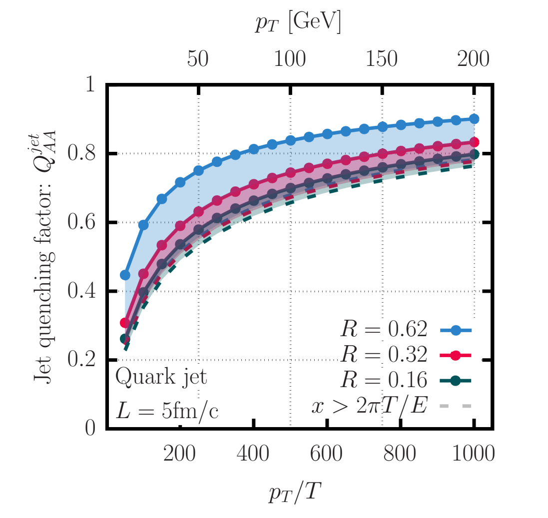
» Taking vacuum spectrum $\frac{d\sigma_{vac}}{dp_T^{in}}(p_T^{in}) \propto p_T^{in\,-\alpha}$

$$\frac{d\sigma}{dp_T} = Q(p_T, R) \frac{d\sigma_{vac}}{dp_T}, \quad \Rightarrow \quad Q(p_T, R) \approx \exp \left[- \int d\omega \frac{dI}{d\omega} \left(1 - e^{-n\omega/p_T} \right) \right] \tag{15}$$

Modeling Jet Quenching

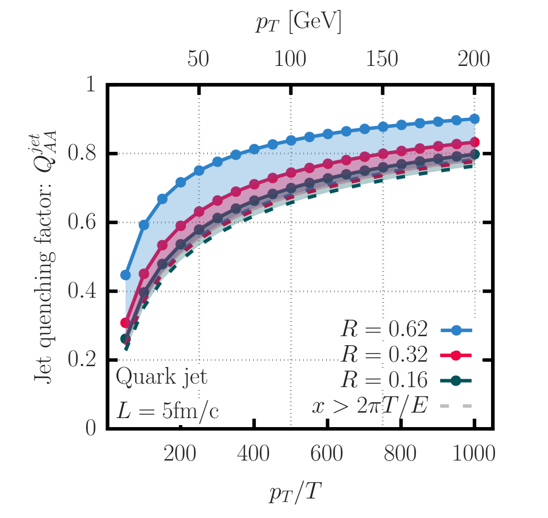
- The first emission is modeled using BDMPS finite medium rate $\frac{d\Gamma}{d\omega}(P,\omega,t)$ at time t
- Medium energy loss computed by modeling the energy remaining inside the cone $E(\omega,R,L-t)$ after a time $(L-t)$ in the medium

$$Q(p_T) = \exp\left[\int_0^L dt \int d\omega \times \frac{d\Gamma}{d\omega}\left(1 - e^{-n\frac{\omega}{p_T}\left[1-\frac{E\left(\omega|R,\tau=\frac{L-t}{t_{th}}\right)}{\omega}\right]}\right)\right]. \tag{16}$$



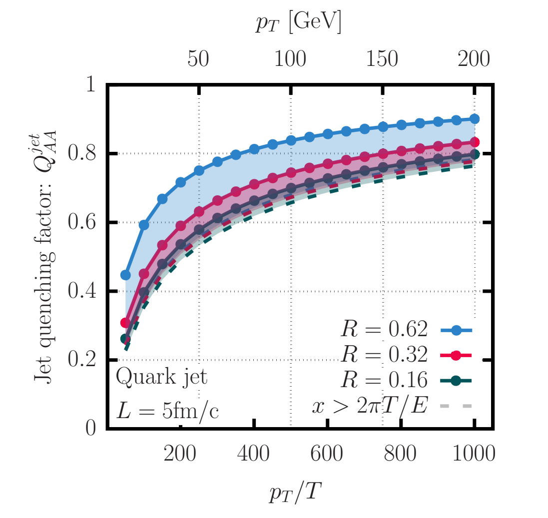
Modeling Jet Quenching

- Jets with energies $p_T \leq 25\text{GeV}$ lose significant energy in length $L = 5\text{fm/c}$
  $\Rightarrow$ large suppression at low p_T, milder for $p_T \leq 200 - 400\text{GeV}$
- Negligible contribution of soft fragments to narrow cone
- Large cone size (≥ 0.3) $\Rightarrow$ Recover energy from the soft sector
  - ▷ Medium response



⊙ Modeling Jet Quenching

- ⚠ Over-estimate energy loss since we neglect finite size effects, Work in progress
- ⚠ Requires more refined studies of near-equilibrium physics and jet recoil onto the medium



Outline

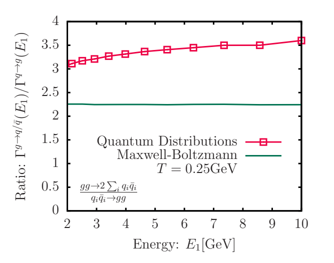
⊙ Flavor Conversion

» Due to scatterings with the medium ⇒ Partons change flavor

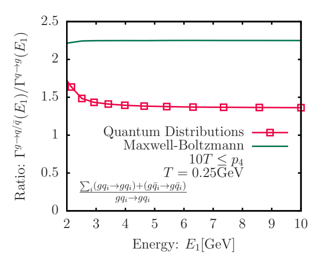
» The rate of flavor conversion is determined by the d.o.f. of the medium

⊙ Ratio of the rate $\frac{\Gamma_{g\to q}}{\Gamma_{q\to g}}$

» Annihilation $gg \to q\bar{q}$



» Scattering $gq_i \to gq_i$



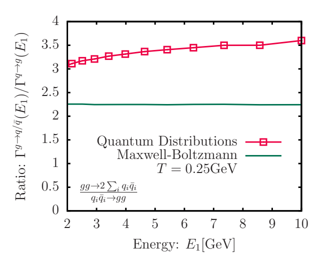
$$\Gamma_{ab\to cd} = \int \frac{d^3\mathbf{p}_2}{(2\pi)^3}\frac{d^3\mathbf{p}_3}{(2\pi)^3}\frac{d^3\mathbf{p}_4}{(2\pi)^3} f_b(\mathbf{p}_2)[1\pm f_c(\mathbf{p}_3)]\frac{|\mathcal{M}_{ab\to cd}|^2}{16E_1E_2E_3E_4}(2\pi)^4\delta^{(4)}(p_1+p_2-p_3-p_4),$$

⊙ Flavor Conversion

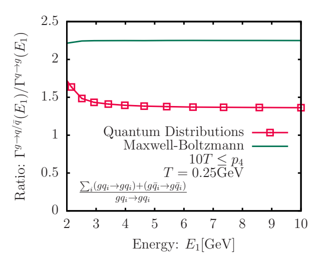
» The rate of flavor conversion is determined by the d.o.f. of the medium

» Since gluon have a larger # partons to scatter of (quarks must scatter with other quarks of same flavor) ⇒ Gluons are converted to quarks at a higher rate than quarks to gluons

» Annihilation $gg \to q\bar{q}$



» Scattering $gq_i \to gq_i$

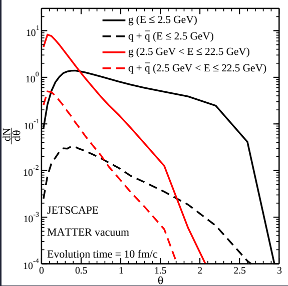


$$\Gamma_{ab\to cd} = \int \frac{d^3\mathbf{p}_2}{(2\pi)^3}\frac{d^3\mathbf{p}_3}{(2\pi)^3}\frac{d^3\mathbf{p}_4}{(2\pi)^3} f_b(\mathbf{p}_2)[1 \pm f_c(\mathbf{p}_3)]\frac{|\mathcal{M}_{ab\to cd}|^2}{16E_1E_2E_3E_4}(2\pi)^4\delta^{(4)}(p_1+p_2-p_3-p_4),$$

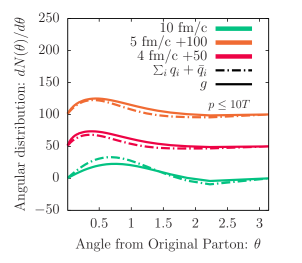
⊙ Flavor Composition Of The Soft Sector

⊙ $E \lesssim 2.5$GeV

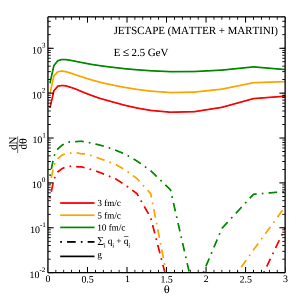
» Vacuum (MATTER)



» Kinetic evolution



» Vacuum + Energy loss (MATTER + MARTINI)



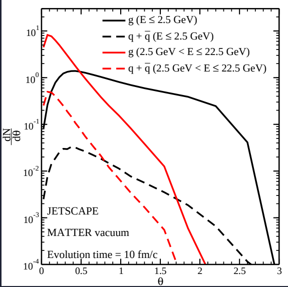
⊙ Flavor Composition Of The Shower

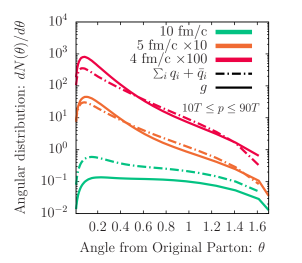
⊙ $2.5\text{GeV} \lesssim E \lesssim 22.5\text{GeV}$

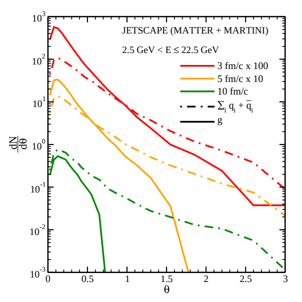
» Vacuum (MATTER)

» Kinetic evolution

» Vacuum + Energy loss (MATTER + MARTINI)





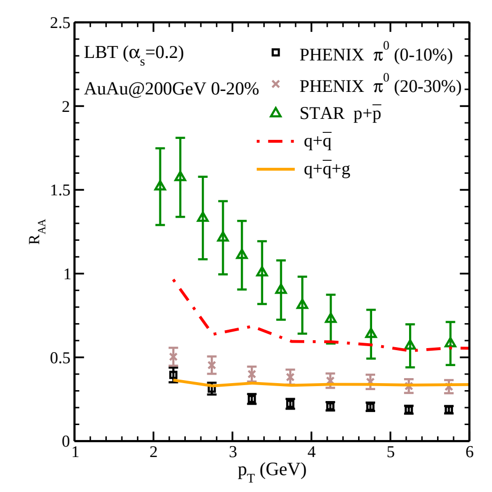


» Quark content of the in-medium shower is much more quark-like than in vacuum

⊙ Flavor Composition Of The Shower

- An order of magnitude increase in the fermion content of jets due to the medium.
- New transport coefficients needed to incorporate quark exchange in jet quenching discussion.
- Increase in fermion content affects conserved charge fluctuations, not energy profile of the jet.

⚠ Hadronization introduces own fluctuations and may introduce additional energy loss. (Work in progress)



Conclusion

- Energy loss is governed by an inverse energy cascade
  $\Rightarrow$ driven by successive collinear radiation
- Energy deposited collinearly at the soft scales rapidly broadens to large angles
- Kinetic evolution can be seen as a Green's function
  $\Rightarrow$ can be convoluted to obtain more evolved evolution
- Chemistry of jets is highly sensitive to the medium
  $\Rightarrow$ several interesting effects at play: baryon enhancement, QGP chemistry, etc.

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Thank you for your attention \o/
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